HIGH STRAIN-RATE DEFORMATION AND FRICTION MELTING AS A POSSIBLE ORIGIN FOR "SHOCK" FEATURES IN ALLAN HILLS 84001. C. H. van der Bogert and P. H. Schultz, Department of Geological Sciences, Brown University, Box 1846, Providence RI 02912, USA.

Summary: Many of the debates regarding the martian meteorite ALH 84001 address the questions of the temperature and age of carbonate deposition [e.g., 1–3] and its ultimate effect on the generation and preservation of evidence for life [4]. To fully answer these questions, we must determine the processes that formed the textures in the meteorite and what implications they have for the environment of carbonate deposition. Discussions of the history and origins of the textures in ALH 84001 have been synthesized by [1], [3], [5], and [6] among others. All such histories propose the occurrence of shock melting and metamorphism for ALH 84001 despite nonunique evidence for shock. Here we present an alternative mechanism for the formation of crush zones in ALH84001, which may also explain the occurrence of feldspar, silica, and carbonate melts.

Introduction: One of the puzzling aspects of ALH84001 is its shock state. Treiman [5], in his interpretation of the shock history of ALH 84001, describes the orthopyroxene clasts within the granular bands ("crush zones" of [1]) as having irregular or undulose extinction, pervasive microfracturing, and polygonization. These observations, coupled with the presence of maskelynite and a glassy matrix lead [5] to propose that ALH 84001 underwent shock levels equivalent to S5 or S6 of Stöffler et al. [7]. Their classification scheme, however, requires the analysis of olivine grains rather than orthopyroxene grains, owing to the wide-ranging nature of shock deformation in orthopyroxene [7]. The presence of melt veins, pockets, and dikes must occur along with high shock indicators in olivine and maskelynite to warrant a classification of S5 and S6 materials [7]. As further illustrated by friction melting experiments in meteorites, the presence of veins of melted materials alone cannot be used as a unique indicator of a high shock process [8]. Unfortunately, the presence of olivine in ALH 84001 is limited and its origin unconstrained [e.g., [9,10]. Consequently, the classification scheme of [7] is not directly applicable.

Minerals show even less evidence for shock outside the crush zones. Scott et al. [3] observe only minimal mosaicism of the pyroxenes outside of the zones. As a result, they interpret shock pressures outside of the crush zones to be small, whereas shock pressures of greater than ~50 GPa are thought to be required for the melting and mobilization of silica and plagioclase melts [11] within the crush zones [3]. It is suggested that these shock pressures would be lower if the target rock were warmer [e.g., 3,11,12]. However, this scenario still requires extreme pressure gradients across only millimeters of section from the pyroxenes outside of the crush zones to those within it. Besides the presence of plagioclase and silica melts, there is no other evidence for high shock levels within the crush zones [3].

In addition, no high pressure polymorphs have been identified in ALH 84001; all evidence for high shock pressures is textural. In Shergotty, the presence of glasses with radiating fractures may indicate rapid quenching from high pressure melts and expansion upon decompression [13]. Maskelynite in ALH 84001 and is also normal rather than diaplectic glass [e.g., 14,15]. Shock levels exceeding 80 GPa are inferred for these types of glasses [13]. Raman spectra of martian "maskelynites" in ALH 84001 are similar to those which have been experimentally subjected to only 31 GPa [15]. These observations require either that the glass was totally melted at a higher shock level than that for the formation of diaplectic glass or the melting event included temperatures high enough to melt the plagioclase grains *in situ*.

An Alternative: The presence of glass and deformation textures, yet ambiguous evidence for shock may indicate that an alternate process controlled the petrologic evolution of ALH 84001. Treiman [5] suggested that the crush zones could be generated during high strain-rate deformation or shock associated with either a tectonic or impact event on Mars. Here we suggest that the crush zones and even melts can develop from high strain-rate deformation without high shock levels. Our scenario is based on the evidence for pervasive shear in ALH 84001, while evidence for shock is minimal. For example, [5] describes "augen or ribbon" structures of orthopyroxene within the crush zone, with chromite stringers, which are "wavy or swirled." Small (<10 µm) Fe sulfides are also present in elongated bands within the crush zone [16]. Olivine inclusions are elongate and "boudinage-like" [10]. Such textures are indicators of shear deformation [e.g., 17,18]. In addition, the crush zones themselves have been described as cataclastic, with larger clasts having rounded edges and smaller clasts with sharper edges [3]. These observations along with evidence for recrystallization suggest that these crush zones are pseudotachylites or friction melts, which are a type of high strain-rate rock typically associated with ultracataclasites [e.g., 19]. In fact, Treiman [5] notes that the crush zones could texturally "be called recrystallized mylonite or pseudotachylite". Further, "the structures of the granular bands are typical of dynamic recrystallization (high strain rates), which can occur during rapid tectonic motions or during shock" [5]. Scott et al. [3] note that the "crush zones were probably heated and welded by friction during crushing, as in pseudotachylites." Such comments coupled with the absence of shock features support a high strain-rate rather than shock origin.

The best terrestrial analog for ALH 84001 is a terrestrial ultramafic pseudotachylite, which occurs in the Balmuccia peridotite, Ivrea-Verbano zone, northern Italy. Textures in the pseudotachylites of the Ivrea-Verbano zone closely resemble the textures observed in ALH 84001. These pseudotachylites contain several distinctive features: dynamic recrystallization; chaotic cataclastic to mylonitic textures; olivine and pyroxene with undulose extinction and densely spaced laminar kink bands; and hornblende locally replacing pyroxene which shows undulatory extinction [20]. The pseudotachylite zones occur in two types: (1) fault vein type, which are parallel to the deformation plane, and (2) injection vein type, which are anastomosing and can form networks of veins [20]. The wall rocks show a high degree of recrystallization, which drops off sharply away from the pseudotachylite vein [20]. These observations, along with small amounts of interstitial glass [20], closely resemble the petrography of ALH 84001. Additionally, the temperature, due to frictional heating, during pseudotachylite formation exceeded 1300 K, which was adequate to almost completely melt the minerals within the shear zone [20]. Such petrographic features are quite similar to those selected criteria used to define a shock state for ALH 84001, and further suggest that ALH 84001 underwent high strain-rate deformation and friction melting, rather than severe shock.

Treiman [5] proposes that the textures in ALH 84001 are likely the result of a shock event rather than a tectonic event on Mars because the random orientations of the crush zones are not typical of tectonic fabrics and because there are more impact than tectonic features on Mars. Large-scale friction melt bodies, however, are associated with large craters on Earth such as the Sudbury structure, Ontario and the Vredefort structure, South Africa [e.g., 21]. These pseudotachylite bodies, though impact related, do not necessarily show evidence for shock. They have anastomosing zones and veinlets, similar to those described in the Balmuccia peridotite, which can explain the random orientation of crush zones in ALH 84001 while still allowing for an origin other than shock. Furthermore, high strain rate experiments on meteorites suggest that non-shock-related melting can occur during impacts [8]. High-strain-rate processes with potentially low shock levels that occur during impact include superfault formation during the modification stage of crater formation [22] and impact-directed material flow during oblique impacts [23,24].

Conclusions: The pervasive high strain-rate metamorphic textures similar to those in a terrestrial ultramafic pseudotachylite, lack of conclusive shock classification, and the absence of high pressure polymorphs, all lead us to propose that the "shock" features in ALH 84001 may instead reflect high strain-rate deformation and friction melting with minimal shock. High temperatures created during deformation can account for recrystallization textures, melting plagioclase grains in situ, and for generating plagioclase, silica, and carbonate melts. The friction melting process is also an effective mechanism for dispersing melts and blebs of metals and metal compounds along shear zones [8]. This process could take place in a tectonic setting similar to the Balmuccia peridotite, northern Italy, or during the formation of pseudotachylite bodies like the Sudbury and Vredefort pseudotachylites. The deformation and melting also may have occurred during the event that ejected the meteorite from Mars. This scenario does not exclude the presence of shock features within the pseudotachylites; rather, it does not necessitate their presence.

The absence of high pressure shock features requires that ejection occurred at low shock levels. Also, if the plagioclase glass formed prior to ejection, temperatures during ejection cannot exceed those which allow the recrystallization of plagioclase glass (e.g., 900°C for one hour [25]).

In agreement with previous studies [3,5], the crush zones are likely impact related. Here, we consider the possibility that the textures preserve a high strain-rate process that allows both localized high temperatures and low shock levels. For example, the crush zones and melt veins may be related to the launch process or preexisting pseudotachylite bodies sampled by the event.

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